Title: Broad Bandwidth Metamaterial Antireflection Coatings for Measurement of the Cosmic Microwave Background

Team Members:

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Research Objectives

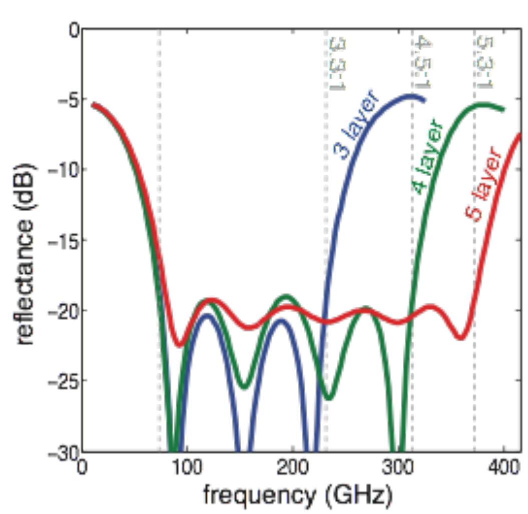
Goal: Develop metamaterial antireflection coatings with broad bandwidth (>3:1 ratio bandwidth), low reflectance (<1%), and negligible dielectric losses for large diameter (> 30 cm diameter) cryogenic silicon and sapphire optics intended for CMB instruments. (The requirements set out in STRO-ESI topic 3)

Innovation: The principal innovation is development of ability to reliably and efficiently cut a large number of small scale features (between 10 and hundreds of microns) in large curved silicon and sapphire substrates with micron accuracy.

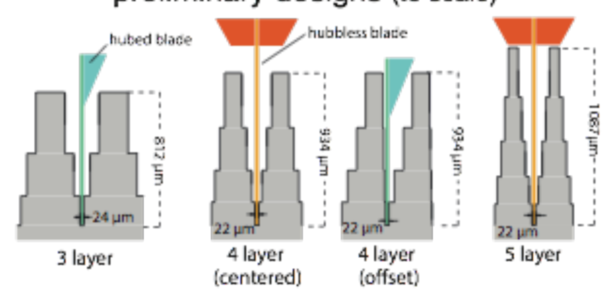
Comparison to SOA: Our group has fielded 1.5:1 ratio bandwidth metamaterial AR coatings on the silicon lenses (up to 33 cm diameter) on the ACT observatory as part of ACTPol project. The proposed work will extend this technique to realize coatings with broader bandwidth on silicon and coatings for sapphire as will be required for future missions using next generation multichroic detectors.

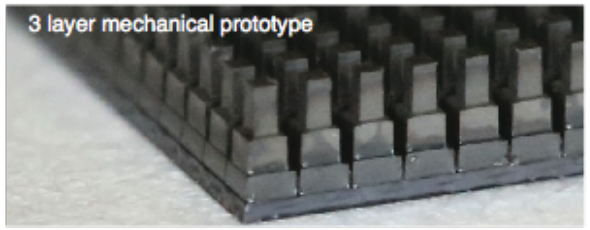
TRL Assessment: The proposed coatings require cutting more complicated features into silicon and developing ability to cut sapphire or bond silicon to sapphire. Achieving TRL 3 requires demonstrating three critical functions (1) fabricating a 30 cm prototype, (2) cryogenically cycling to verify survivability, and (3) performing optical measurements to verify performance. Currently the simplest broad band silicon coatings are TRL 2 (5 cm prototypes fabricated, but no demonstration of these critical functions) and the sapphire coatings are TRL 1 as no tests have been performed.

multilayer AR coatings simulations



preliminary designs (to scale)





This figure shows preliminary designs for broad-bandwidth metamaterial coatings fabricated directly from silicon including: simulations (left), preliminary designs including an illustration of how a saw can cut the deepest and smallest features (top right), and a mechanical prototype for the simplest of these designs (bottom right). The proposed work will: (1) demonstrate these coatings on large (30 cm) optics, (2) provide precise measurement of their reflection and transmission to confirm their optical performance, and (3) verify their robustness to cryogenic cycling.

Approach

There are three development areas for this proposal: (1) broad band coatings, (2) scaling these to cover the CMB frequency bands from ~30 to 600 GHz, and (3) developing ability to coat sapphire half wave plates. Our plan is as follows:

Broad Band Coatings: Three multilayer coating designs with >3:1 ratio bandwidth are shown in the figure at the center of this page. The difficulty in fabricating these coatings increases rapidly with the number of layers. We will fabricate 30 cm diameter prototypes of the 3, 4, and 5 layer designs, subject these samples to cryogenic cycling, and optically test these prototypes to achieve TRL 3. The fabrication of 3 layer coatings (mechanically prototyped to TRL2) minimizes development risks, and the 4 and 5 layer coatings allow for increased bandwidth performance (as shown), or ability to optimize for even lower reflections over 3:1 ratio bandwidth.

Frequency Scaling: We will scale the best performing broad-band design up by a factor of 2 in frequency and down by a factor of 3 to demonstrate coatings across the key frequencies for the CMB: from ~30 to ~600 GHz.

Sapphire Coatings: We will optimize our design for birefringent substrates (eg sapphire) and attempt two fabrication methods: direct machining, and bonding silicon to sapphire to permit fabrication of the coatings in the easier to machine silicon layer.

Potential Impacts

The proposed coatings will solve a broad class of problems related to dielectric optical elements in the millimeter and sub-millimeter wave bands including lenses, wave plates, lenslet arrays, and potentially novel optical elements such as antireflection coated volume phase gratings.

Silicon is a particularly attractive material for millimeter and far-infrared optics as it has a high index of refraction (n = 3.4) and extremely low dielectric losses permitting novel wide field optical designs. Sapphire is birefringent and can be used to realize low loss wave plates. By fabricating our coatings directly from the silicon and sapphire substrates we can create coatings that are cryogenically and mechanically robust and inherit the extremely low dielectric losses of the parent materials.

Applied to a future CMB experiment in the form of reimaging optics on a ~1.5 meter reflecting telescope, this technology could enlarge the usable field of view, and provide a compact cold stop cooled to ~1 K. Our calculations show that this would boost mapping speed by more than a factor of two, improving the science return of future satellite observatories.

This technology is also applicable to astrophysics missions (Calysto), Earth Observing missions (potentially BLISS for SPICA), SOFIA instruments, and national defense by enabling compact mm and THz imagers for concealed threat detection or THz spectrometers for remote explosives detection.